Fast Readout Optical Storage Technology (FROST) Consortium

Contract # F-30602-98-3-0226
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Consortium Members:
- Call/Recall, Inc.
- Irvine Sensors Corporation
- University of Southern California

Other Participating Institutions:
- University of California, Los Angeles
- Parallel Solutions, Inc.

Objective:

- to develop and demonstrate VLSI Photonic technologies capable of addressing the limiting bottlenecks in digital optical storage systems.
- to develop a bit-oriented removable optical volumetric disk system with a parallel readout head to demonstrate high-capacity (**50 Gbyte per platter**), and high-throughput (**2 Gb/s sustained user data rate).**

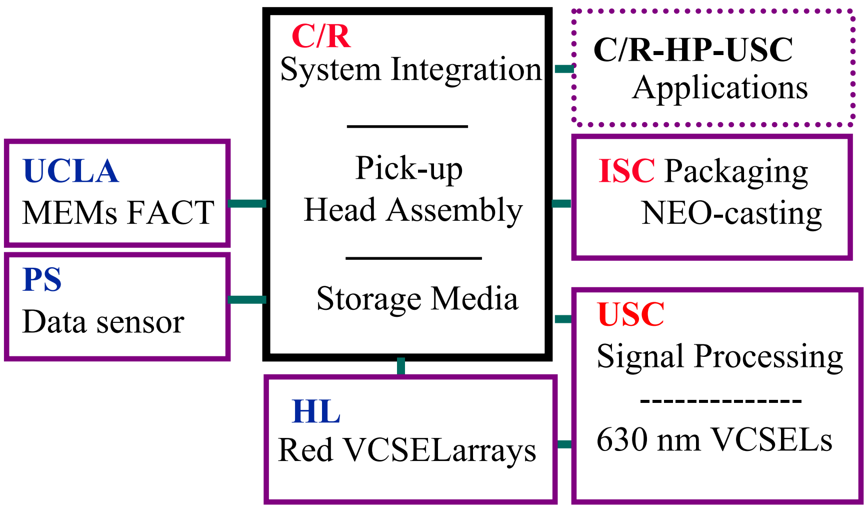
Approach:

Utilize a volumetric disk readout architecture based on

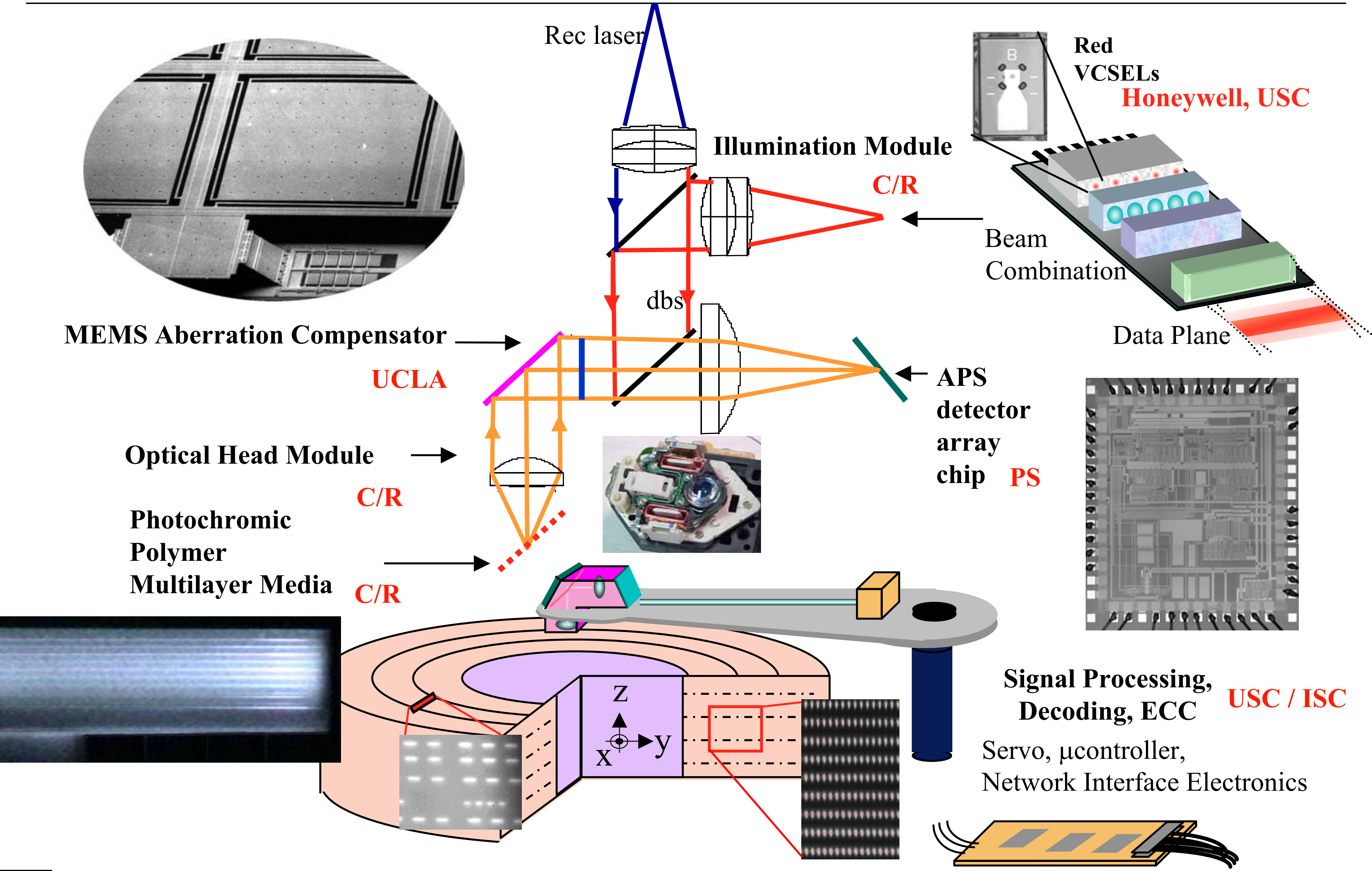
- photochromic polymer storage media,
- VCSEL array,
- 3-D imaging system,
- MEMS optical actuator chip,
- high-performance sensor array,
- parallel channel electronics,
- micro-bench optical packaging.

Program Milestones:

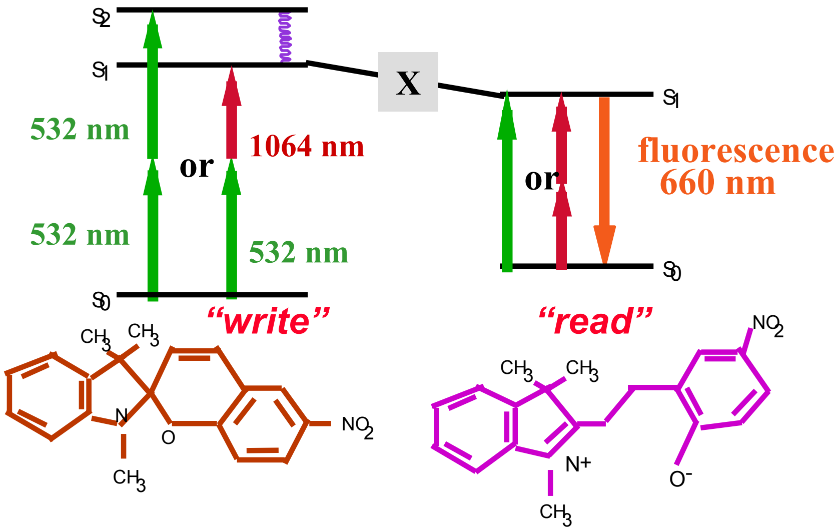
1999: Components & Subsystem Designs:
media, VCSELs, receivers, MEMS
2000: Illumination subsystem module
2001: Imaging mod. & Subsystem integration:
Low speed sys. demo
2002: Single supertrack high speed demo
2002: Radial access final demo



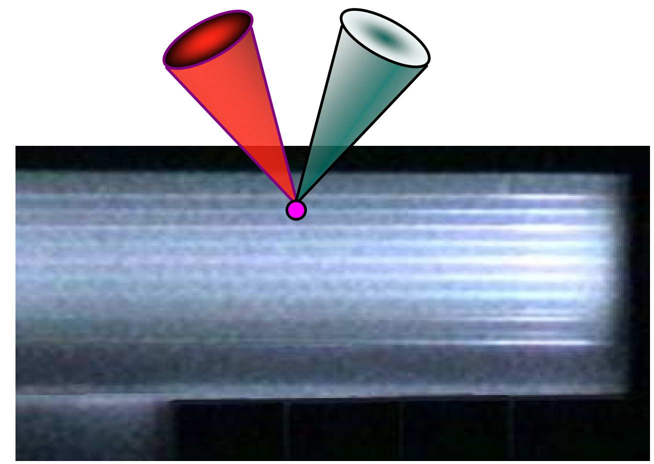
FAST READOUT OPTICAL STORAGE TECHNOLOGY:
Parallel access multilayer optical disk data storage

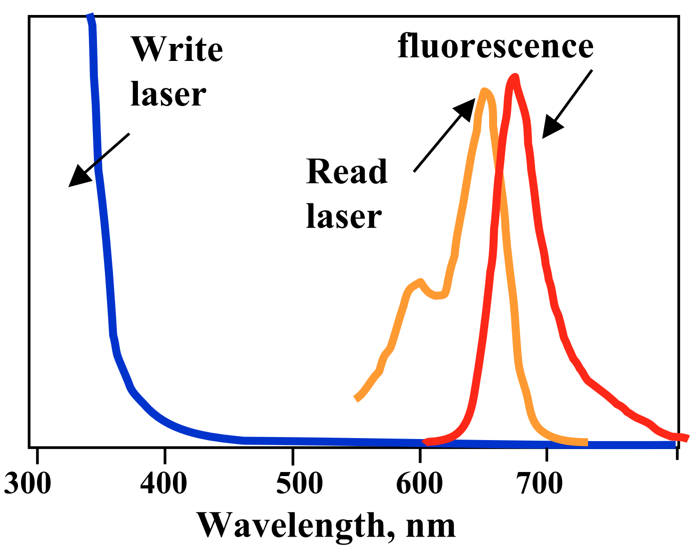


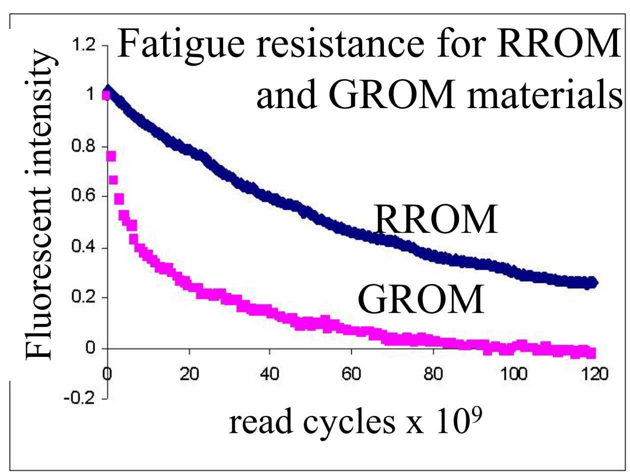
Two-photon sensitive WORM media operation and characteristics

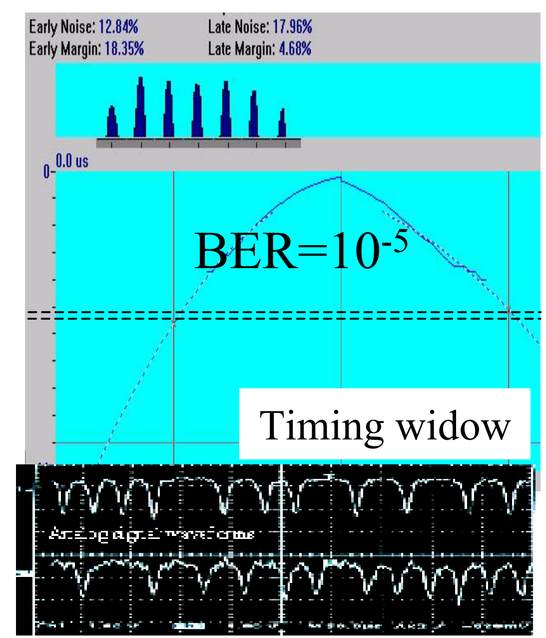


Non-written molecule *Written molecule*

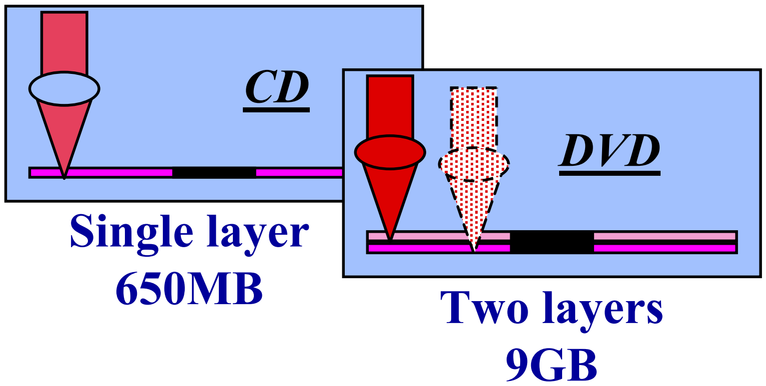


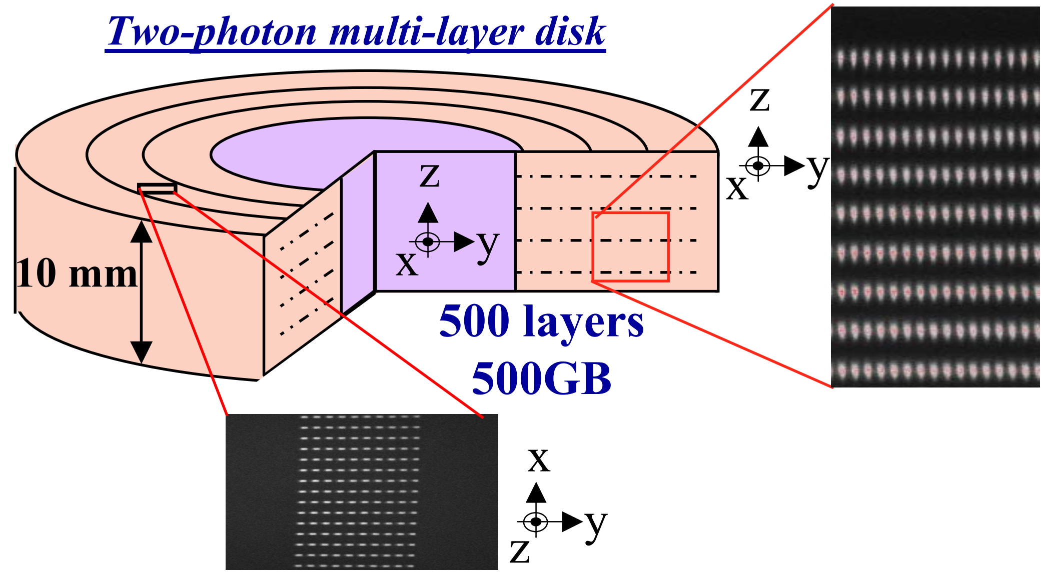






3D Disk Capacity and Data Rate





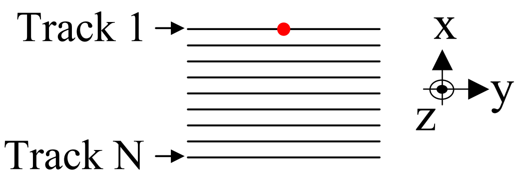
Blue DVD

λ = 410nm
NA = 0.85
Spot size= 1.22 λ /NA=0.6 μm
layers= 2
Layer pitch = 40-70 μm
Capacity = 45 GB
Rate = 35 Mb/s

Two-photon (Blue) multi-layer disk

λ = (460nm) / 635nm (write)/read
NA = 0.5
Spot size = ~1 μm
layers = 500
Layer pitch = 20 μm
Capacity = 500 GB
Rate=(1Mb/s/ch)(1000 channels)=1 Gb/s

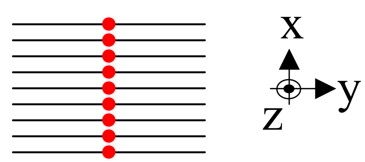
Parallel readout architectures



- **<u>Single spot</u>:**

- simple, low cost

- low data rate, large stroke actuator

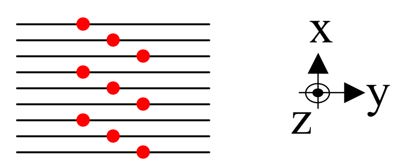


•<u>1-D array (single layer)</u>:

- increases transfer rate

- more complex track/focus

- poor use of FOV of lens

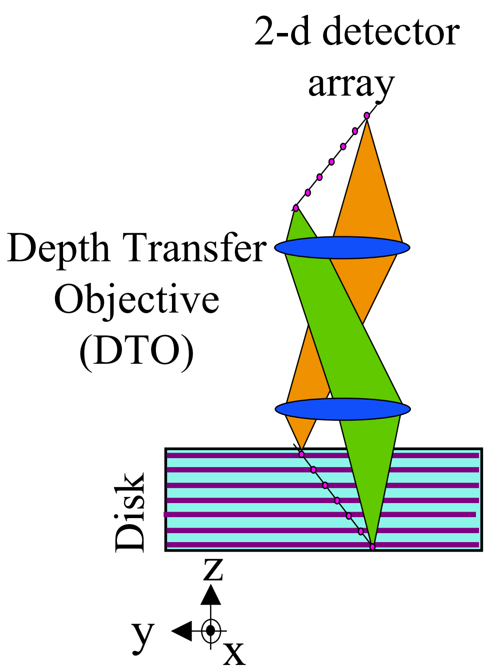


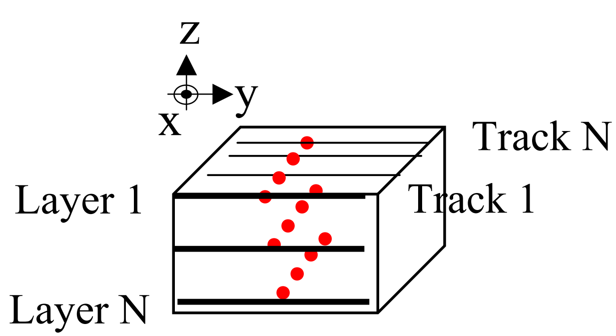
<u>2-D array (single -layer)</u>:

- 1-D issues plus

- CAV

- same throughput as 1-D array





<u>2-D array (many layers)</u>:

- multi-track/multi-layer readout

- high transfer rate

- BEST use of lens 2-D FOV

- minimizes actuator stroke

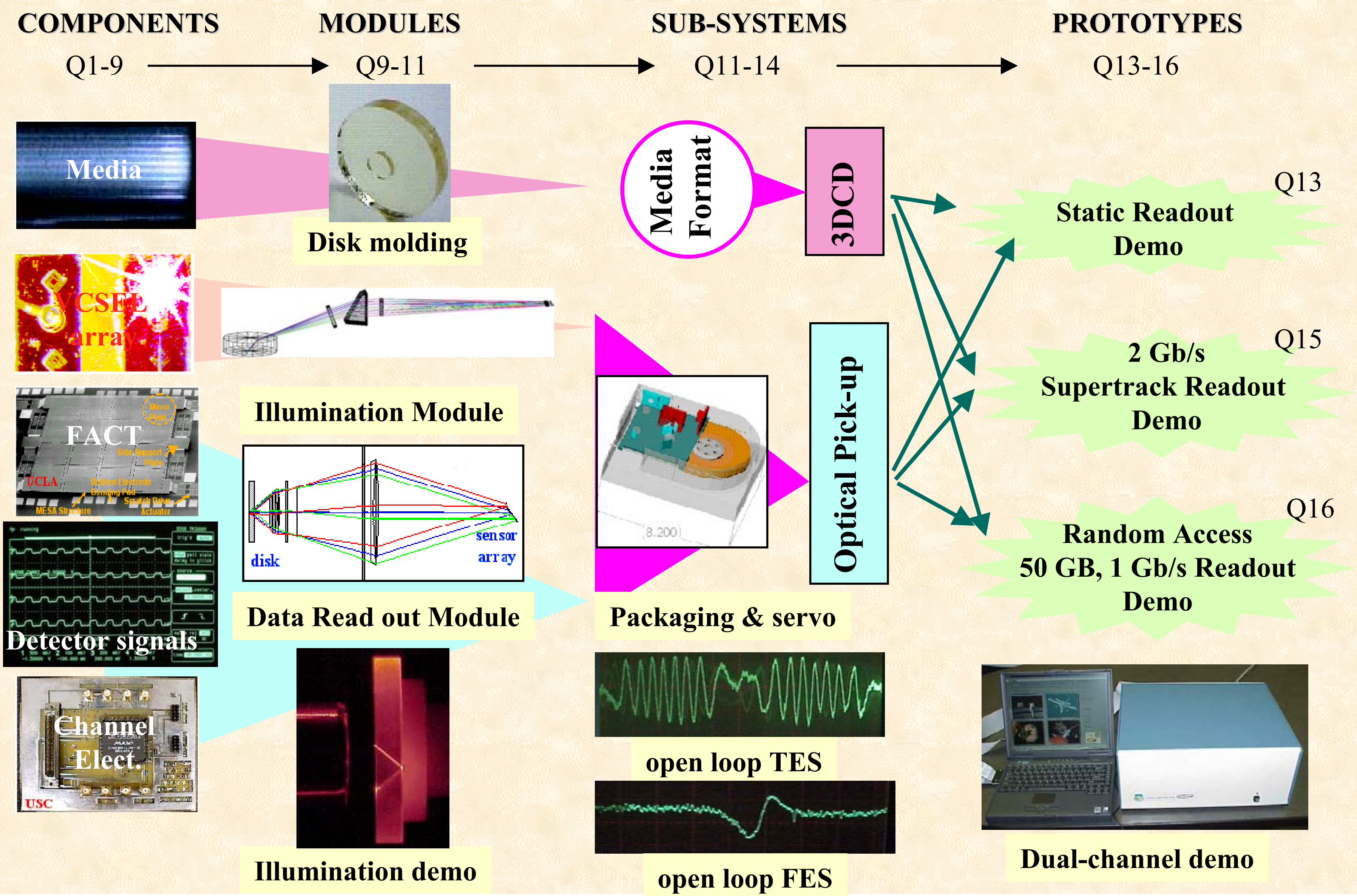
- CLV

- More complex track/focus

- 3D media and novel optics

Depth Transfer Objective (DTO):
Doubly telecentric afocal image relay images data plane with constant lateral and longitudinal magnification to the detector array

FROST Program Flow

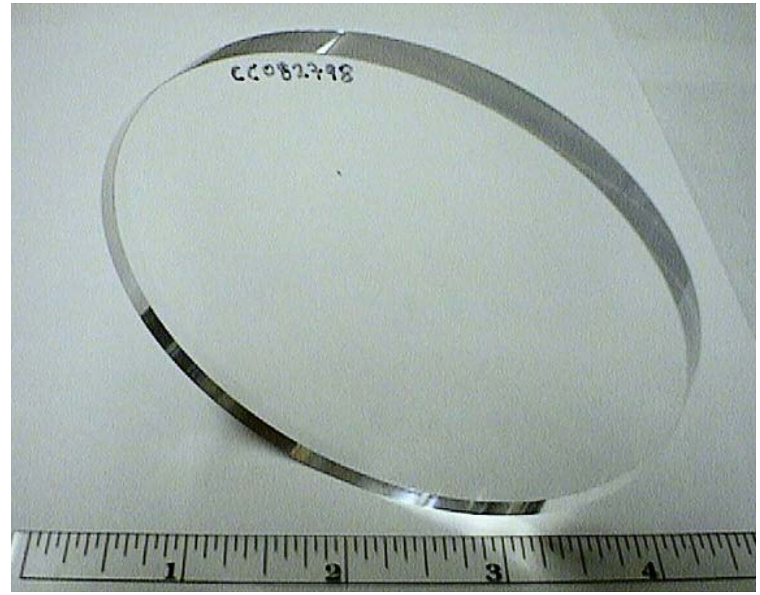


Thick Disk Media

OBJECTIVE

5.25" diameter red readout thick disk media for FROST to achieve

- **Read form absorption tuned to red VCSEL wavelengths**
- **increased sensitivity and improved performance characteristics**



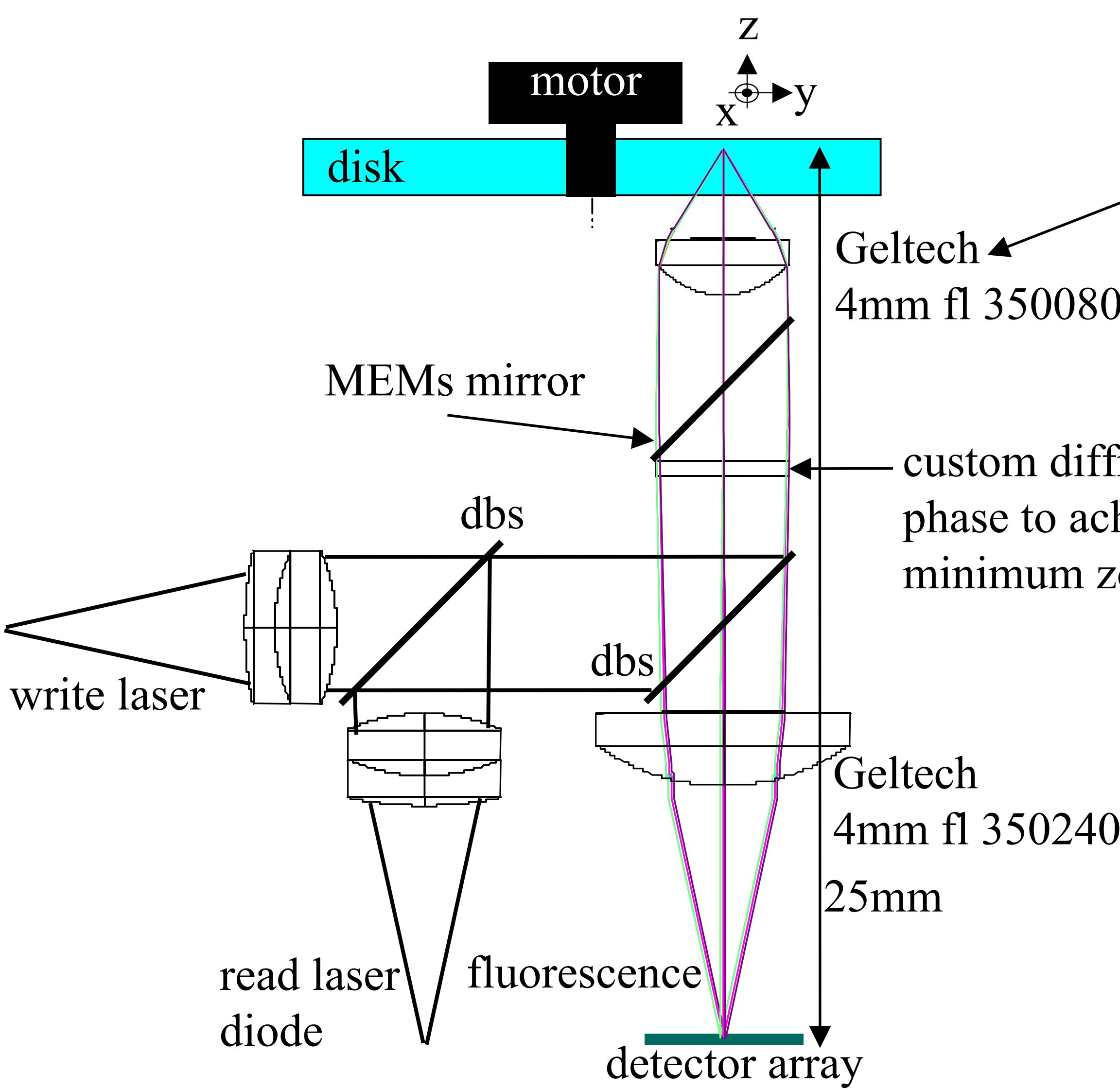
APPROACH

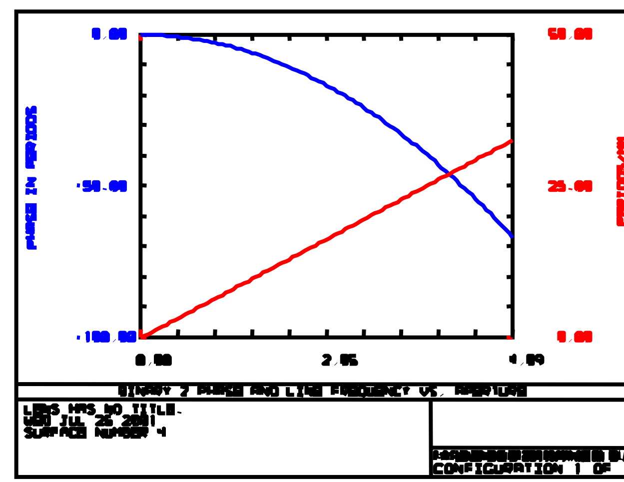
- **Photochromic-dye-doped polymers**
- **Volumetric Storage**
- **Highly efficient fluorescence**
- **Broad write/read λ-tolerance**
- **Single beam recording with very closely spaced layers**
- **Low cost moldable plastics supporting ultra high density media**

3rd YEAR ACCOMPLISHMENTS

- **Readout with red (650nm) diode laser**
- **3.5 inch diameter, 5mm thick disks fabricated**
- **3X Higher writing efficiency**
- **10X Lower background noise**
- **3X Higher readout fatigue resistance**
- **Higher temperature stability**

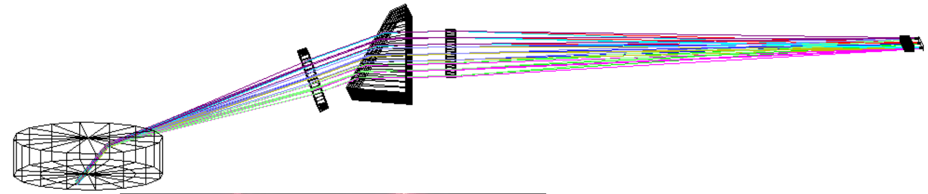
0.53 NA DTO system architecture with collinear recording and illumination paths

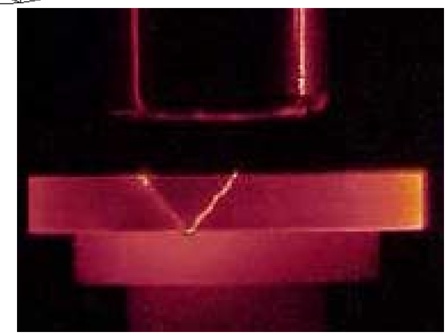


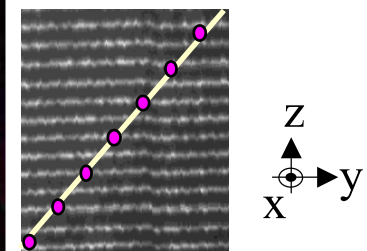


Illumination Module

OBJECTIVE
To illuminate a 2-dimensional data page inside the disk to generate fluorescence from a selected data page containing 1024 data channels





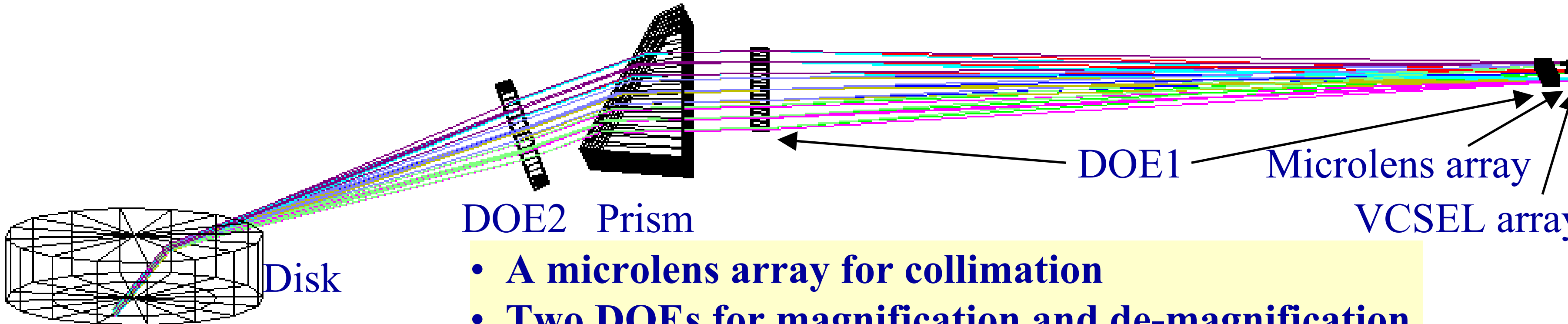


APPROACH
- By combining a 2-d VCSEL array output into a uniform sheet of light.
- By imaging a 2-d VCSEL array to a data page on a point by point basis

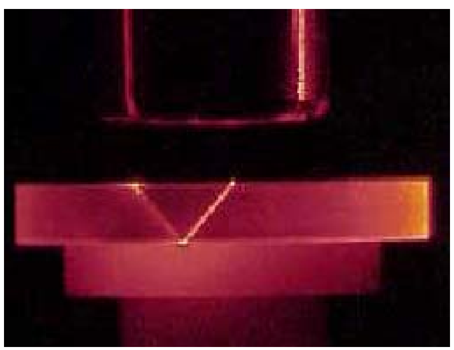
3rd YEAR ACCOMPLISHMENTS
- Demonstrated beam sheet of 20µm x 160µm x 300µm
- Demonstrated a 1x16 point by point illumination
- 2-D custom and cots designs completed

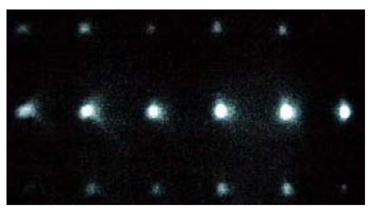
Illumination Module

For multi-track/multi-layer parallel readout

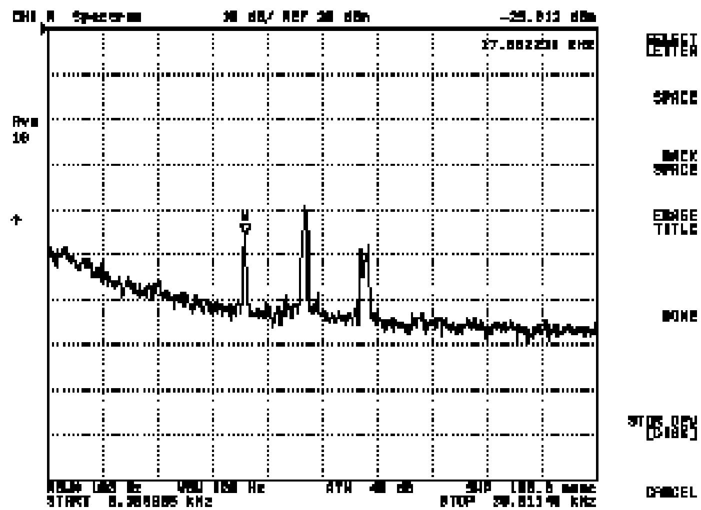


- A microlens array for collimation
- Two DOEs for magnification and de-magnification
- A prism for deflection
- A DOE for focusing and aberration compensation





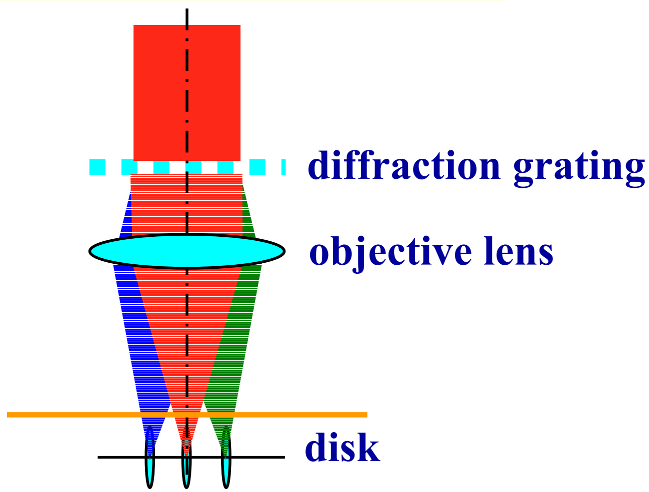
six tracks
(20μm interval
at a same depth)

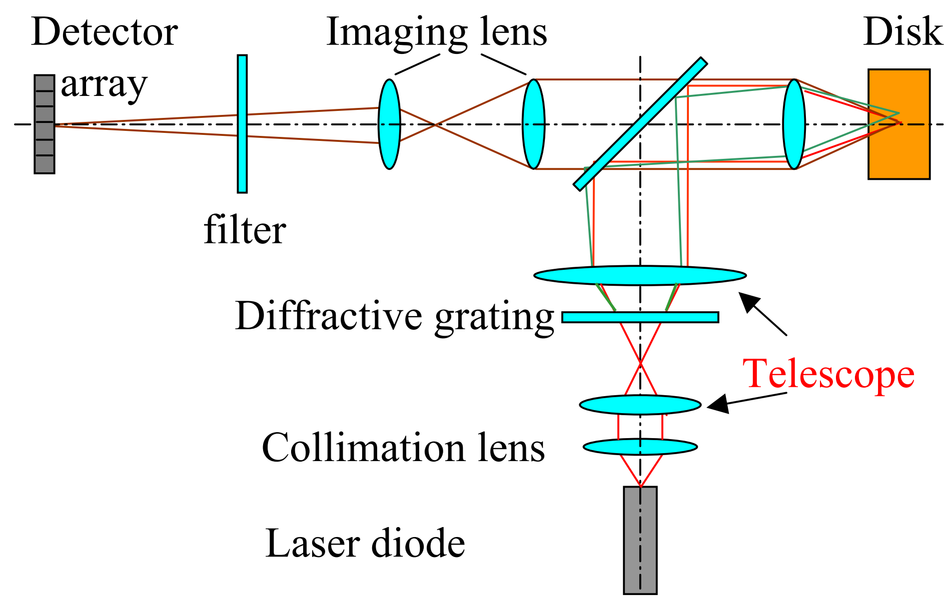


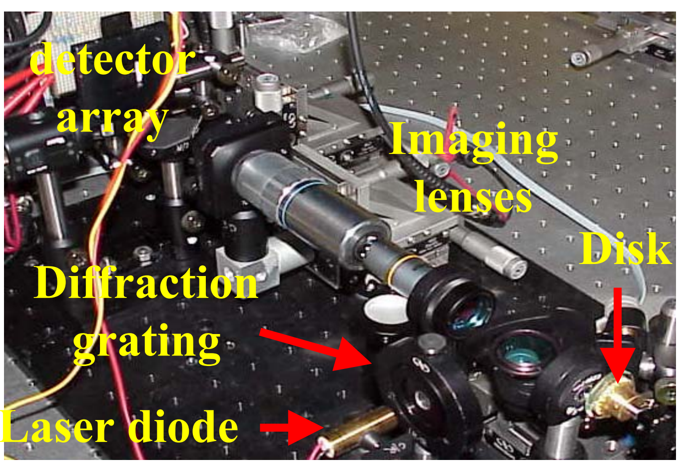
Readout of three tracks
(75μm interval along the depth)

One Dimensional In-plane Parallel Readout

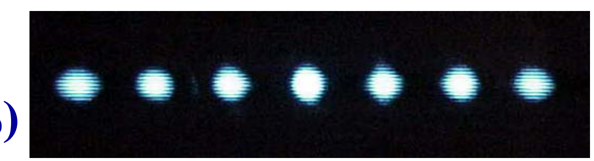
diffraction grating generates in-plane spot array.







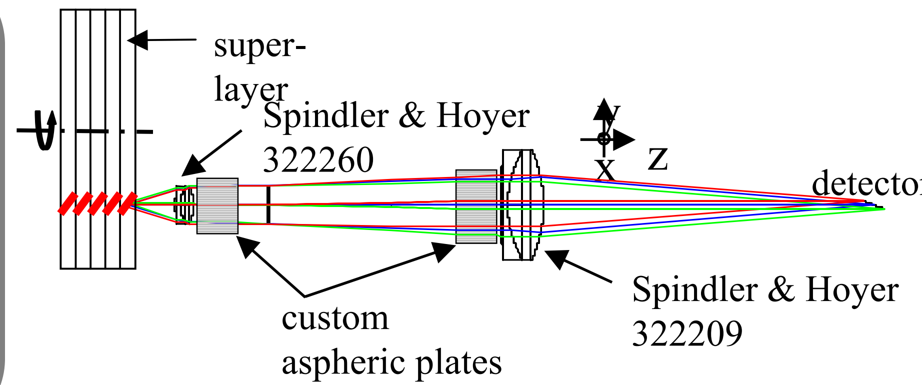
Spot array
(power: ±10%)



Parallel readout of 7 channels. (in-plane parallel readout)

Depth Transfer Optics

OBJECTIVE
Collect fluorescent emission of 1000 data channels and image to detector array to achieve increased data throughput



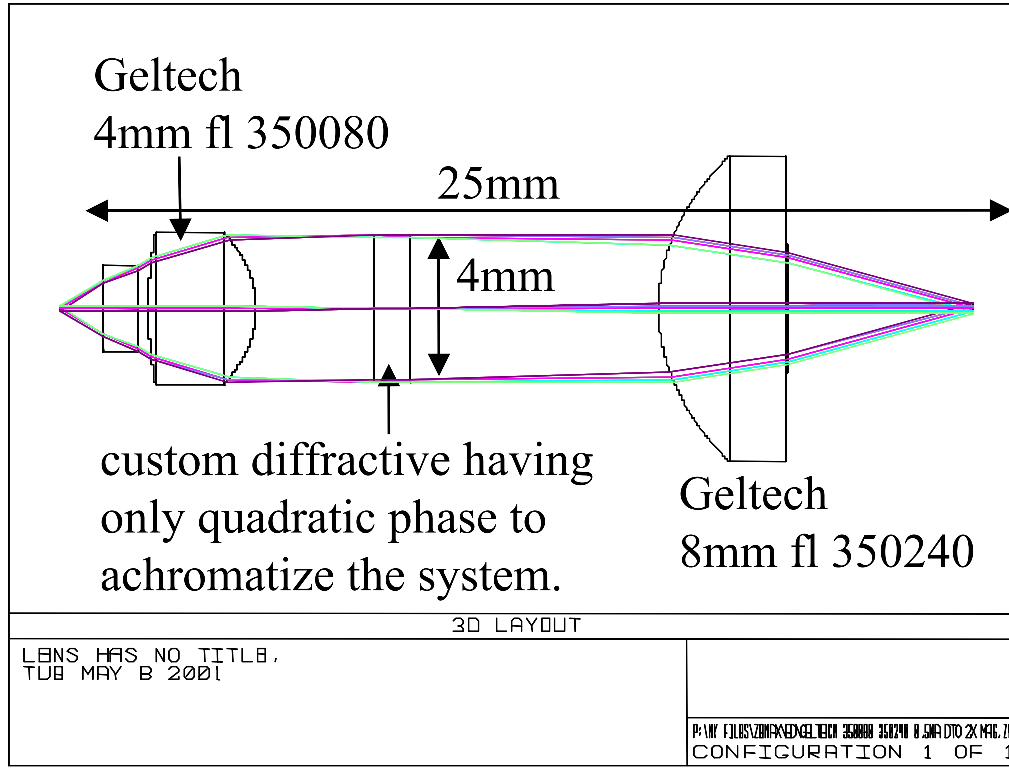
APPROACH
- By using commercially available and custom optical components in a Depth Transfer Optical imaging system.
- multi-layer/multi-track parallel readout

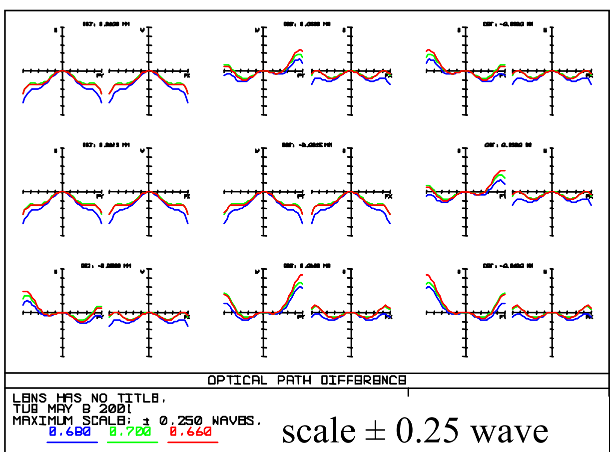
3rd YEAR ACCOMPLISHMENTS
- Integration of components
- New 0.5 Optical system design with 120µm object field, 2.5x magnification.
- Standard cd/dvd voice coils for servo integrated in design.

0.53 NA DTO design (incorporating commercially available and low cost custom components)

System properties

- NA = 0.53
- magnification m = 2
- Object field 120µm
- initially corrected for ~1.2mm of material thickness
- object to image distance ~25mm
- can accommodate up to ~ 3 mm of disk thickness
- achromatic from 0.66µm – 0.7µm





- Higher performance than current 0.3NA design
- custom diffractive is manufacturable
- need to tolerance system
- shorter than previous system

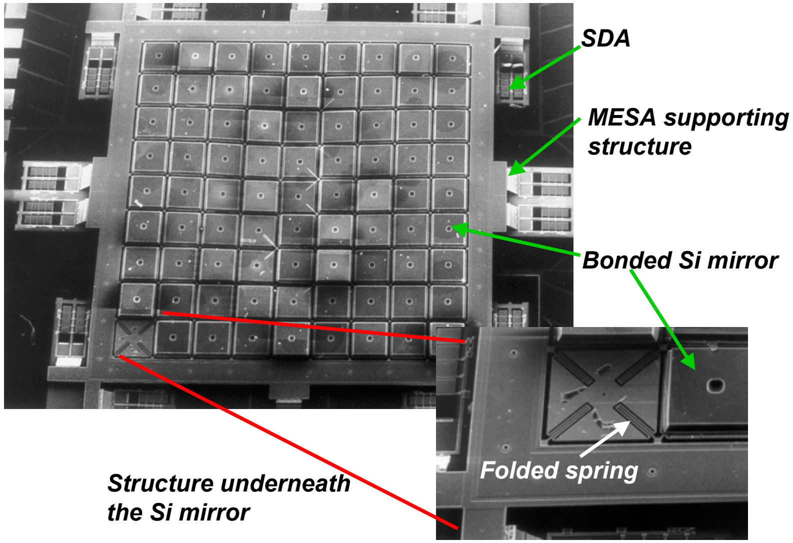
MEMS FACT

Fast Aberration Correction Technology

OBJECTIVE

Develop MEMS deformable mirrors for FROST to achieve

- Active control of focusing and tracking for optical pickup head
- Low cost and feasible MEMS Tip-tilt micromirror arrays (MTMA)



APPROACH

- By using commercial-available foundry service to fabricate low-cost prototype MEMS mirror arrays actuators
- Novel bonding process to transfer stress-free single crystalline silicon mirror onto MEMS actuators

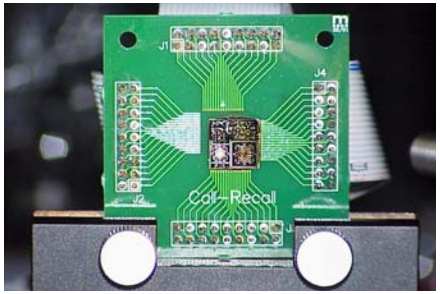
3rd YEAR ACCOMPLISHMENTS

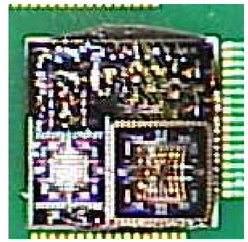
•Developed wafer-scale batch transfer process to fabricate smooth and flat mirror surface

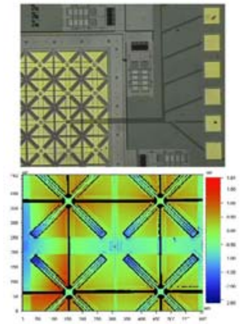
•fabricated low cost MEMS deformable mirrors with long stroke (~10 μm) and large aperture (3 mm)

Optical testing of deformable mirror for aberration compensation

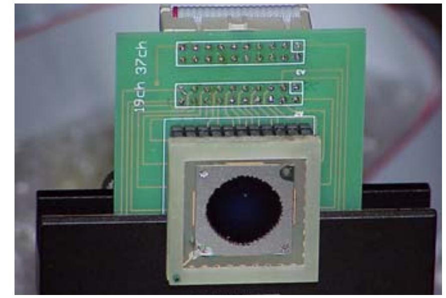
UCLA Mems mirror

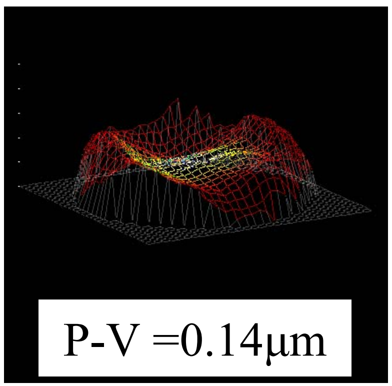


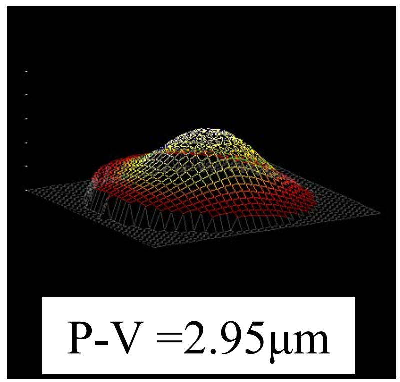


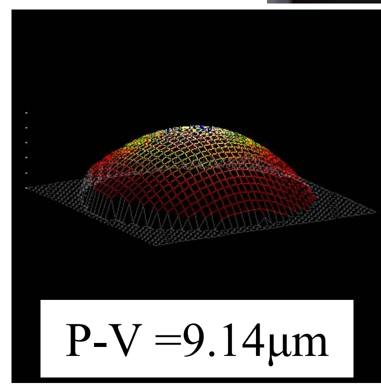


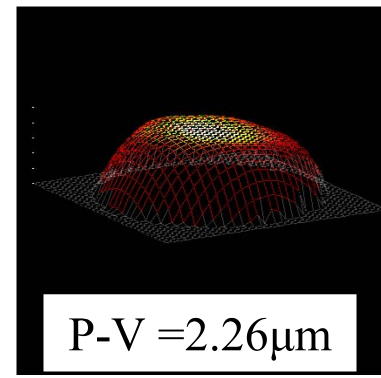
OKO deformable mirror

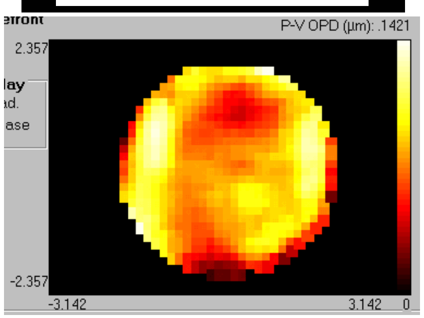


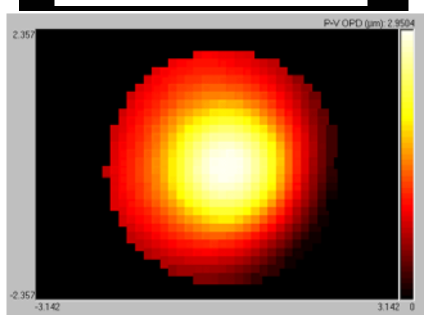


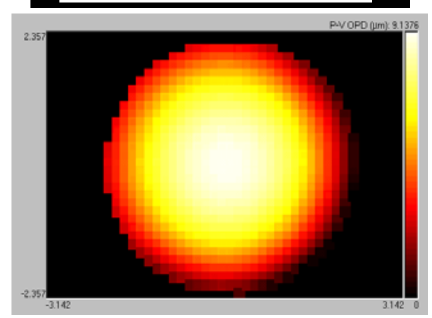


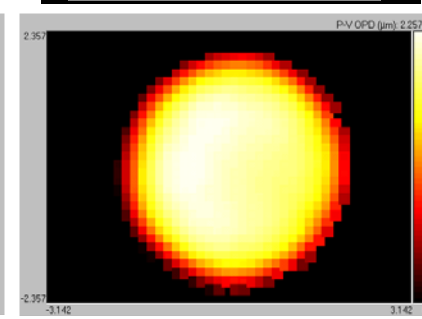










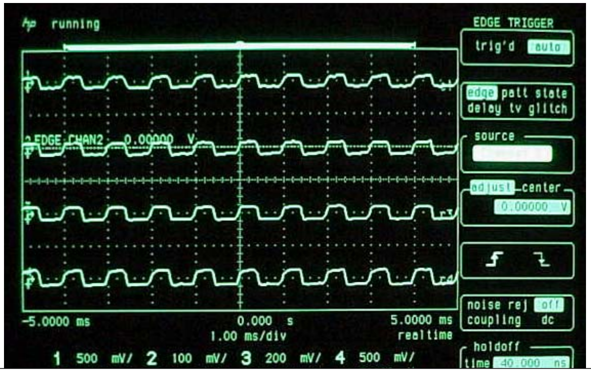


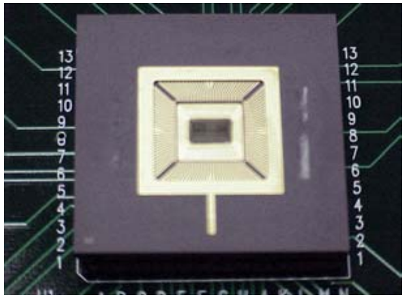
- 9µm of defocus introduced on wavefront, resulting in ~70µm of axial movement in 0.5NA system. 2µm of spherical aberration correction.

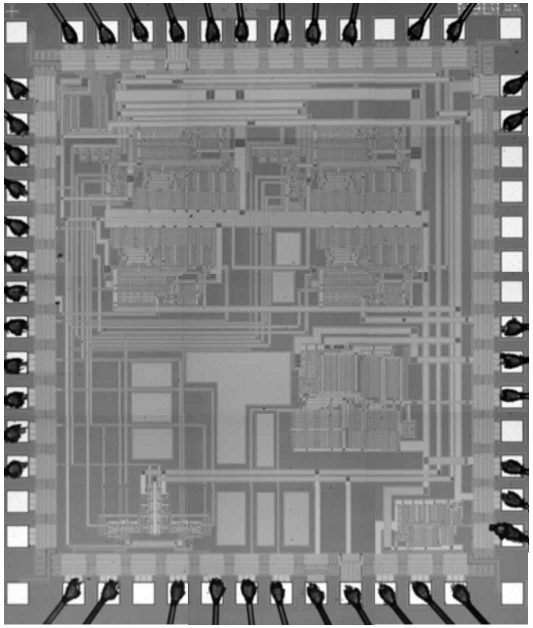
Low Light level Sensor array

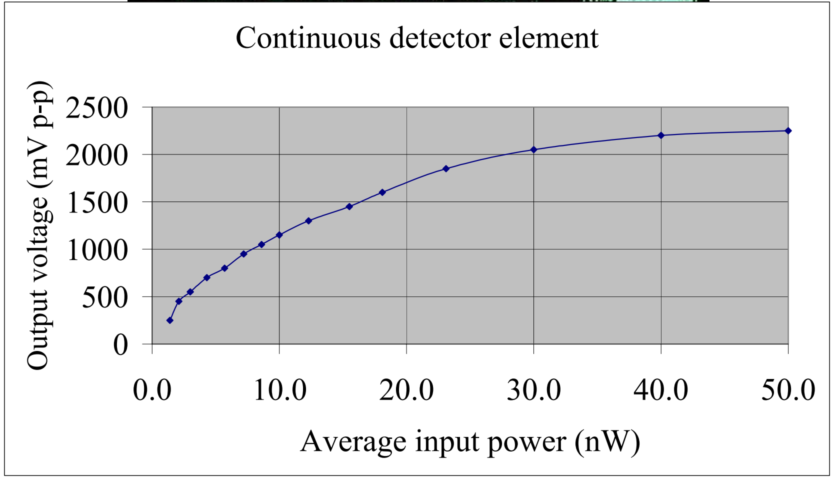
OBJECTIVE

Develop 5MHz hi sensitivity (3000 photons) parallel detector array
(CMOS Active Pixel Sensor)





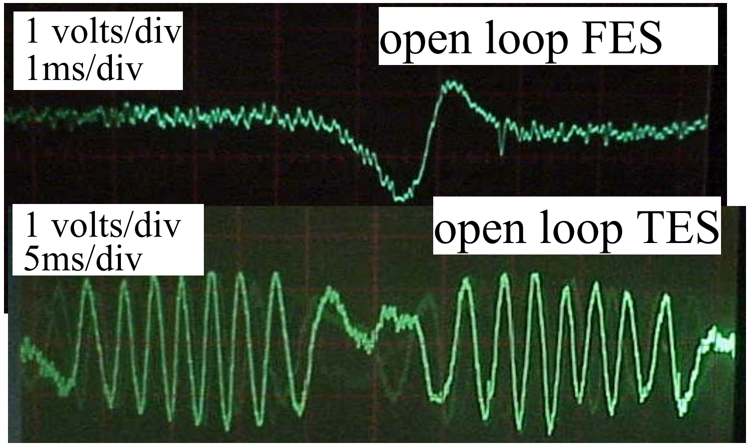




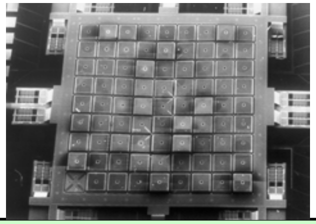
3rd YEAR ACCOMPLISHMENTS

- very low noise performance with ~2000 photon signals measured
- Test chip fabricated in MOSIS 0.5μm process and received from MOSIS
- Characterization of test chip

Servo



OBJECTIVE
Maintain the DTO and illumination beam position on the same page, super-layer/super-track addressing, maintain spindle speed
- for removable media
- for mechanical drift



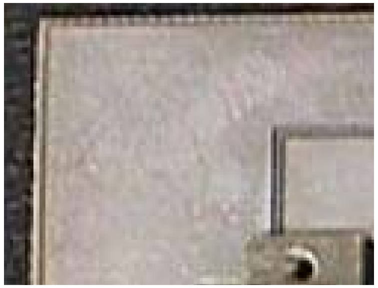
3rd YEAR ACCOMPLISHMENTS
- closed-loop focus and tracking control developed for two-photon media.
- no preformatting of media required
- illumination and recording servo conceptualized and being developed.

APPROACH
- use standard voice-coil actuators.
- serial data channel
- then integrate MEMs devices
- extend to parallel data format

Read Channel Data Flow

OBJECTIVE

Decode 1024 parallel data channels
- Develop optimum encoding/decoding algorithms for parallel readout
- Optimize code for material characteristics



Dual Channel Decoder

COTS ECC chip

APPROACH
- By using commercial chips
- Small scale testing of low number of channels to aid in evaluating required performance.
- extend to 1024 channels

3rd YEAR ACCOMPLISHMENTS
- 16 channel readout system using programmable encoding/decoding
- Decoding System on an FPGA reconfigurable computing engine
- simulation tool to model ISI including detector, media,and DTO imaging system parameters.

FROST Year 3 accomplishments

- Synthesized and characterized material with 3 times higher writing efficiency. Demonstrated that the material supports sub-micron size bits.
- Demonstrated a WORM system capable of 8 channel parallel readout with 8Mb/s readout speed.
- Demonstrated detectors on APS with fluorescence from disk media and measured sensitivitiy for 2000 photons.
- 9x9 Mems mirror array from UCLA currently being integrated into DTO
- Serial closed-loop focus and tracking control optimized and extended to parallel channels.
- New Illumination and Depth Transfer Objective designs for thick media completed. Illumination beam of 20μm x 160μm x 300μm sheet of light demonstrated. 0.53NA Depth Transfer Objective with diffraction-limited performance across a 120μm object field designed.

FROST Year 4 plan

- **Transition developed components into module and subsystem demonstrations.**
- **Demonstrate 4 x 16, 64 channel DTO readout system. (Next quarter)**
- **Design illumination beam and collection optics focus and tracking servo systems to handle 1024 parallel data channels.**
- **Submit a 1024(16 x64) active pixel sensor chip for fabrication**
- **Single track demo of 1024 parallel channels with 2Gb/s readout speed.**
- **Random access demonstration of a 50Gb capacity ROM disk with data transfer rates of 2Gb/s**
- **Packaging requirements will be continuously revised.**